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SEISMOLOGICAL LABORATORY 252-21

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ANNUAL PERFORMANCE REPORT

"Planetary and Primitive Object Strength Measurement
and Sampling Apparatus"

NASA/Washington Grant NAGW-2439

for the period 2/1/95 - 1/31/96 (year two)

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Appendix A: Thomas J. Ahrens - Summary Curriculum Vitae

Appendix B: Ronald F. Scott - Curriculum Vitae

ABSTRACT

Support is requested for continuation of a program of dynamic impact (harpoon) coring of planetary, comet, or asteroid surface materials. We have previously demonstrated that good quality cores are obtainable for planetary materials with compressive strengths less than 200 MPa. Since the dynamics of penetration are observable on a Discovery class spacecraft, which images the sampling operation, these data can be used with a model developed under this project, to measure in-situ strength and frictional strength of the crust of the object. During the last year we have developed a detailed analytic model of penetrator mechanics and submitted a paper on this subject to the *Journal of Geophysical Research*.

Measurements of dynamic friction forces are to be conducted next year for both hollow (core tube) and solid penetrators. Initial experiments on a spall chip penetrator indicate a need to improve sample retention components. This development is to be conducted during the next year's program. Devices which withdraw core samples from asteroidal, planetary or cometary materials will also be developed. We believe this project is demonstrating that for both soft and hard planetary materials, the dynamics of impact sampling, in addition to providing samples provide quantitative in-situ strength data.

I. INTRODUCTION

Present expectations are that within the next decade, penetrator emplacements of instruments followed by sampling programs to several possible regions on Mars and also primitive objects (comets and asteroids), e.g. the proposed Phoebus/Deimus Sample Return Mission, are likely to be initiated in the context of the small mission - Discovery program. It has been long recognized that the small-scale cratering efficiencies on both planetary and primitive bodies are strongly affected by the effective strength of these objects [Holsapple, 1994]. We propose to continue a program to tightly relate impact penetration strength to the ability to sample and emplace instruments, both via impact tube, and spall sampling apparatus, as well as solid penetrator apparatus.

Previously with PIDDP support, we have conducting penetrator core, and solid penetrator experiments characterizing the strength properties of soft and hard targets and developing a first principle theoretical model of impact penetration and impact core sampling (Caltech model) [Anderson et al., 1995]. This model requires dynamic friction data which have never been measured for planetary materials at high strain rates. The present request is for FY 96 funding for the project.

We have tested the Caltech model over a range of parameters which include penetration strength from 2 to 200 MPa and frictional strength from 1 to 12 MPa. These mechanical properties are believed to be characteristic of impact processed planetary materials and affect their estimated cratering age [Neukum and Wise, 1976] because of the relation of cratering efficiency to in-situ strength [Holsapple and Schmidt, 1982; Melosh et al., 1992]. For impact strengths > 200 MPa, characteristic of undamaged igneous rock, we believe it is important to both conduct experiments to verify the Melosh theory of impact spall at low velocities (m/sec) and understand the characteristics of a dynamic sampler. We propose to continue to develop a sampling method based on the concept of impact spall.

The present program began because T. Ahrens lacked confidence that it was possible within our present envelope of knowledge to confidently design landers such as the Champollion (NASA/CNES, Comet lander) and, use a more-or-less conventional apparatus, on a primitive low g object and also obtain a sample by core drilling. As we developed a hollow harpoon core sampling apparatus, it became highly obvious as we constructed analytic models, that the penetration process itself was intrinsically related to penetration hardness and surface frictional properties. These, in turn, are related to elastic moduli and strength utilizing modern theories of crack damage, e.g. Ahrens and Rubin [1993]; Ashby and Sammis [1990]; Grady [1987]. In this proposal we:

- (1) briefly outline our progress during FY 95,
- (2) Outline a proposed program for FY 96, the third (final) year of this project grant.

II. PROGRESS REPORT

We conducted additional laboratory experiments and analytic modeling in FY 95. Progress was made in the three areas outlined below:

a) Solid Penetrators Experiments.

We assembled the results of some 35 experiments conducted under this program on impact coring and penetration into an analytic theory which predicts penetration depth for a wide range of media having nominal compressive failure stresses in the range of 1.5 to 200 MPa (15 bars to 2 kilobars). We found a critical lack of data on penetrators without a central hole, and because of the growing importance of this geometry to proposed missions, especially to Mars and comets, we conducted several experiments with solid penetrators (e.g. Fig. 1) testing our model. As can be seen in Fig. 2, the three new solid penetrator experiments, fit closely to those predicted by the CIT Model.

b) CIT Penetrator Model

Using these data and from some 38 experiments, we constructed the model described in Anderson et al. 1995 which has now been written as a scientific paper and submitted to the *Journal of Geophysical Research*.

This model predicts the dependence of penetration depth on the various parameters of the target-penetrator system, as well as the qualitative condition of the target material ingested by a corer. Penetration depth is approximately inversely proportional to the static bearing strength of the target (i.e., the maximum load the surface of a half-space can support without failure). The bulk density of the target material has only a small effect on penetration, whereas friction is significant, especially at higher impact velocities, for consolidated materials. In this case, deep penetration exposes a

large fraction of the penetrator surface to contact with the target material. This trend is reversed for impacts into unconsolidated materials. For an impact at 500 m/s, varying the friction coefficient from 0 to 0.15 can change the penetration depth by a factor of ~ 3 for typical properties of a moderately weak planetary material such as tuff. The present results suggest that the depth of penetration is a good measure of the strength, but not the density, of a consolidated target. Both experiments and model results show that, upon passage through the mouth of a coring penetrator requires initially porous target material to be compressed to $<26\%$ porosity. Also, the sample collected by the corer will be highly fragmented. If the final porosity remains above $\sim 26\%$, then consolidated media will be collected as a compressed aliquot.

Not surprising, as stated above, a parameter which is not well established, in our model, is the friction as a function of sliding velocity between the sides of the penetrator and different planetary materials. Initial fits to the data in Anderson et al. indicates great sensitivity to velocity which has also been observed in the case of metal upon metal sliding [Bowden and Tabor, 1968]. We propose to examine frictional stresses of penetrator next year as outlined in Sect. 3.

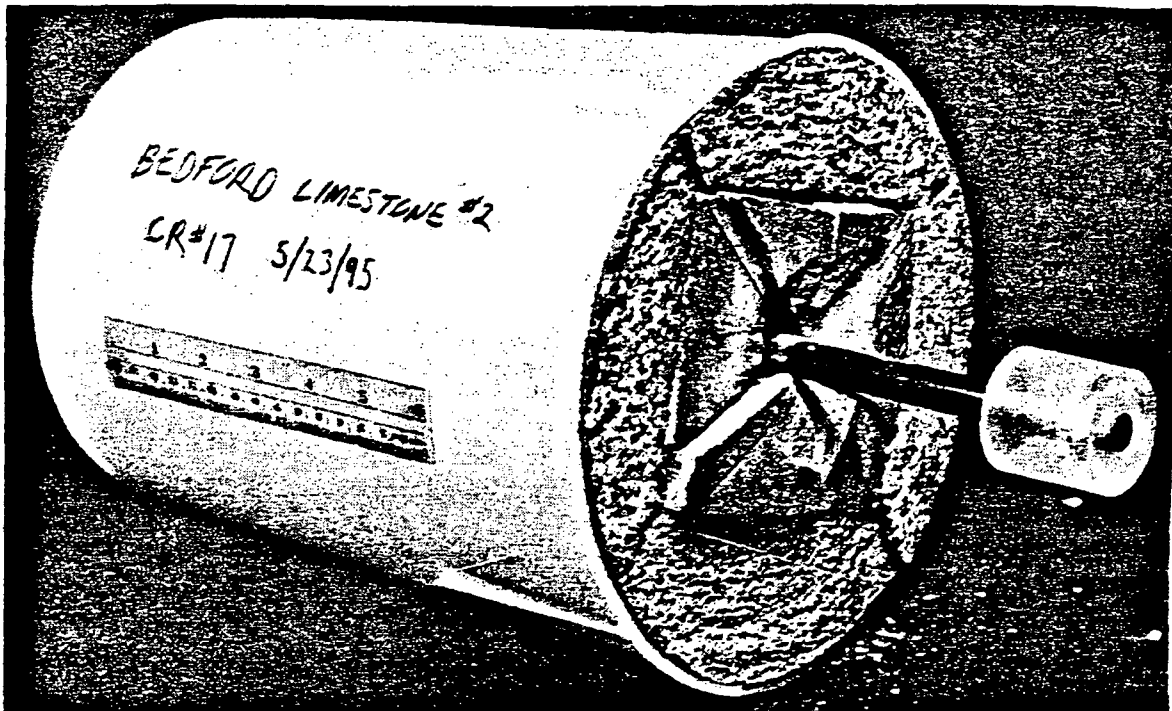


Fig. 1. Solid penetrator experiment. A 12 mm diameter penetrator, 26 cm in length and weighing 170 g, was launched into the target material using the Caltech 40 mm compressed gas gun apparatus. The target consisted of Bedford Limestone (density 2.4 g/cm^3 and hardness, 200 MPa) embedded in a white plastic container of concrete. Penetration of the limestone occurred to a depth of 11.3 cm; and removal of the penetrator required a force of $80 \pm 20 \text{ N}$. The plastic cylinder at the exposed end of the penetrator shaft, is used to sabot the penetrator in the gas gun.

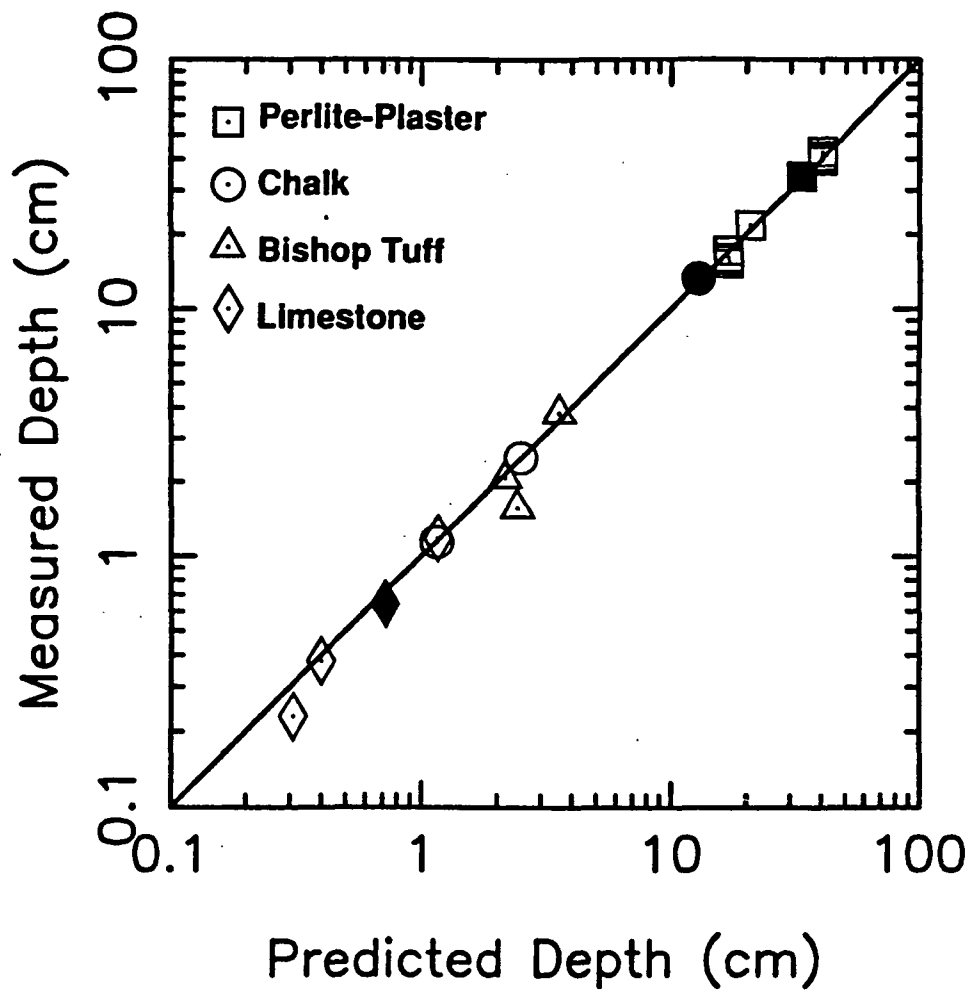


Fig. 2. Comparison of penetration depths predicted by the Anderson et al. [1995] model with those observed in the experiments. Open symbols are for coring penetrators and filled symbols are for solid penetrators.

c) Impact Spall Sampling Apparatus

We have demonstrated that it is virtually impossible to impact harpoon a sample as hard $P_s > 200$ MPa rock such as expected on a differentiated asteroid which lacks a significant regolith. (Differentiated asteroids only a few km across, some of which included in the group of near earth asteroids (which can be reached with a sample return mission) in a Discovery class mission probably lack thick regoliths). To sample asteroids, whose surface may be bare rock, it appears practical to develop a concept of impact spall sampling.

When a geologist impacts a hard rock with a hammer, the rock directly beneath the hammer on impact is pulverized. However, the annular flake of rock surrounding the hammer or impactor is broken loose. This is the usual sample the geologist collects. Impact spall physics which operates because of the tensional failure of the rock beneath the annular flake of the material was first described by Melosh [1984]. His work was motivated by the need to explain how SNC and lunar meteorites could be launched, and yet have little shock damage, from the surface of Mars and the Moon at velocities of >5 and 2.3 km/s. His work motivated experiments to verify the relation of dynamic tensile strength to spall thickness [Lange et al., 1984 (Figure 4)], and the spall velocity related to impactor speed [Polanskey and Ahrens, 1990]. Recently Gratz et al. [1993] conducted a beautiful series of tests demonstrating the pristine nature of spall fragments and directly determined the spall velocity from impact penetration of fragments in a coaxial foam collector cylinder. This foam collector was down range. During the last year we attempted to collect spall samples in up-range foam collectors, such as depicted in Fig. 3, without success. However, we were partially successful with the design shown in Fig. 4. The major problem, which we believe we can overcome is to construct a more robust sample retention mechanism and use a spring retaining sampling impactor as shown in Fig. 5 and the permanent magnets for retention of samples containing magnetic minerals such as kamacite and titanomagnetite are also to be tested as discussed in Sect. 3.

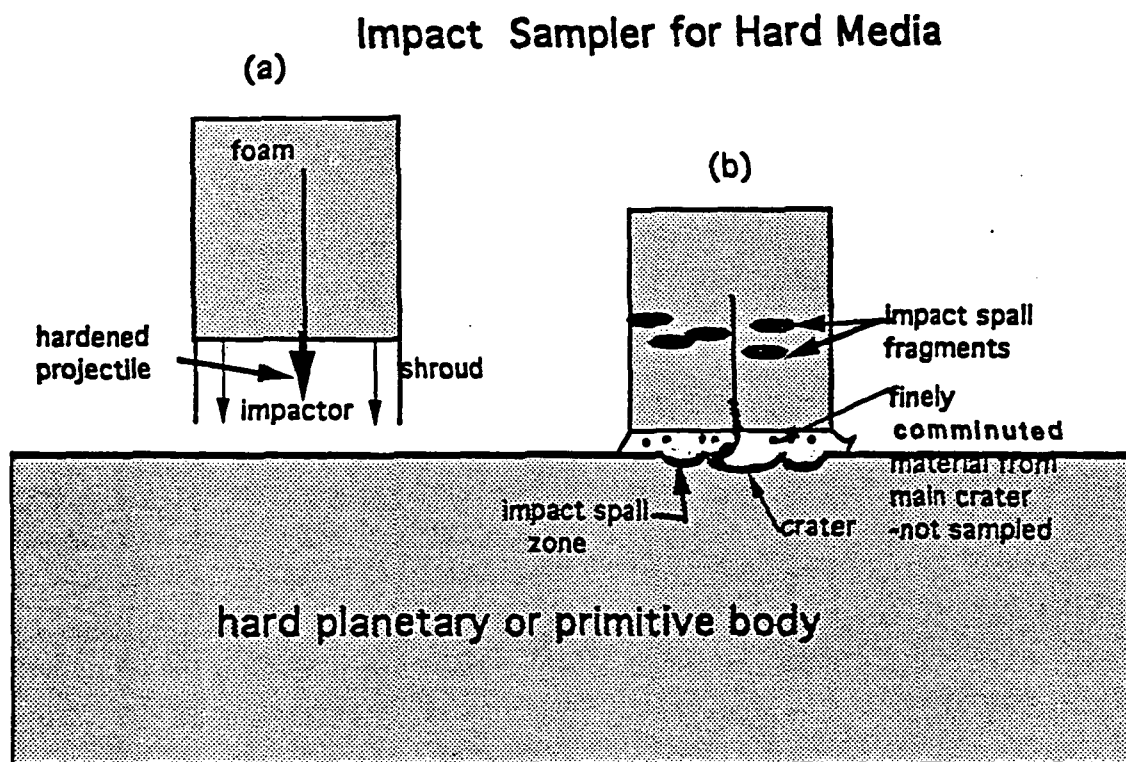


Fig. 3. Concept drawing of impact spall capture hard rock sample apparatus. (a) Hardened tungsten carbide impactor surrounded by plastic foam capture cylinder impacts hard rock surface. (b) Upon impact, central (pit) crater forms. This bowl-shaped region is pulverized. Surrounding surface annular region of flake-shaped fragments are ejected at speeds given by Melosh [1984].

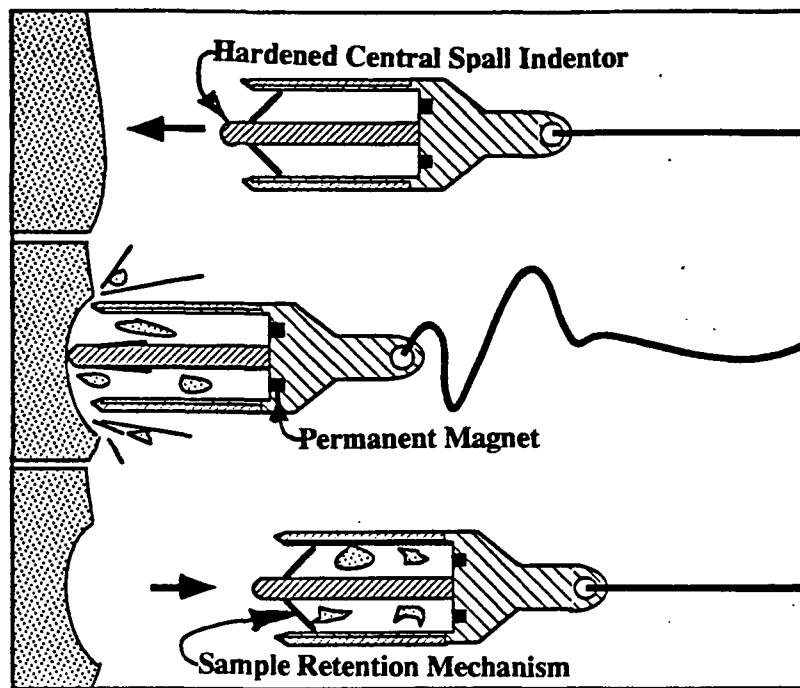


Fig. 4. Spall sampling sequence for a hard planetary target materials (differentiated asteroid or igneous rock).

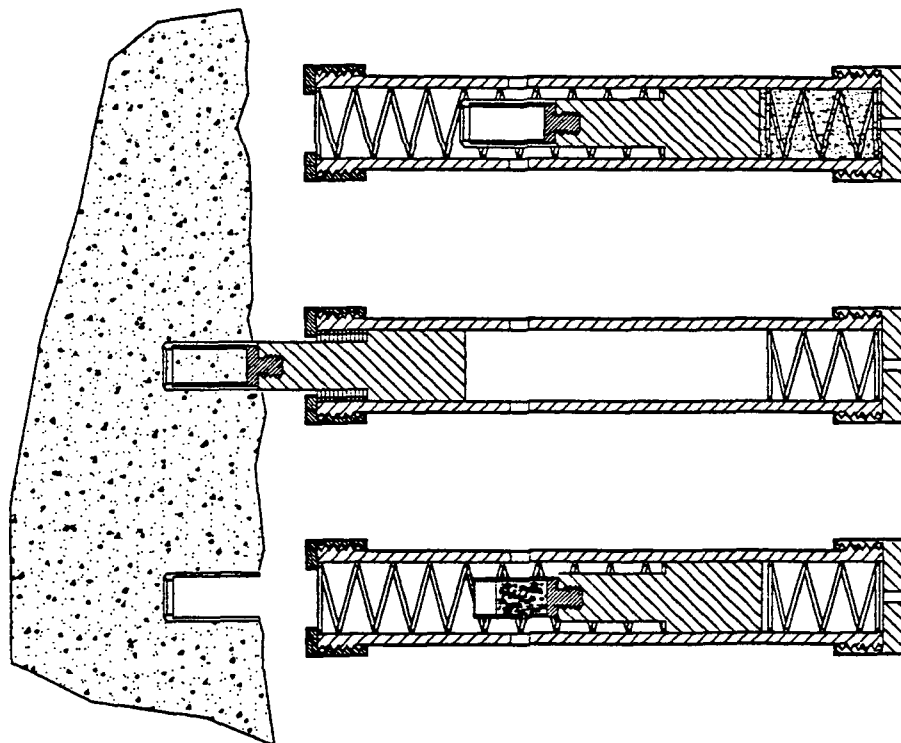


Fig. 5. Propellant driven impact sampling systems, with two-piece penetrator (a portion remains in the sampled object) and the core sample is returned to the sampling boom via the spring shown. This apparatus is currently under construction.

III. PROPOSED PROGRAM

a) Penetrator Dynamic Shear Stresses.

As stated in Sect. IIb, above, we have found a lack of previous measurements of dynamic shear frictional stress data. Under quasistatic stress the coefficient of friction of a large number of earth materials have been reported (e.g. Byerlee [1968]). However, in the case of planetary, asteroidal or cometary penetrators measurements, the amplitude and magnitude of the penetrating stress (cone pressure or stress) and shear stress induced by friction (slide friction pressure) would be useful. However, this class of data are not available for dynamic sliding as it affects penetrators (Fig. 6). In geotechnology such data, at quasi-static strain rates, are useful in characterizing soil media (Fig. 7). We propose to obtain these data under dynamic conditions and apply these to modeling dynamic penetration as, for example, for the model of Anderson et al. [1995].

b) Development of sample retention apparatus for both coring and spalling.

We propose to construct and test dynamic planetary coring apparatus employing retraction springs as sketched in Fig. 5, as well as more robust versions of a spall sample retainers (Fig. 4). We expect to also develop theoretical models of the spring tensions required to break-off cores of different tensile strengths using the crack-damage versus tensile relations developed by Ahrens and Rubin [1993]. In the case of spall collection of rock fragments we propose to relate sample size to the impact spall theory developed by Melosh [1984].

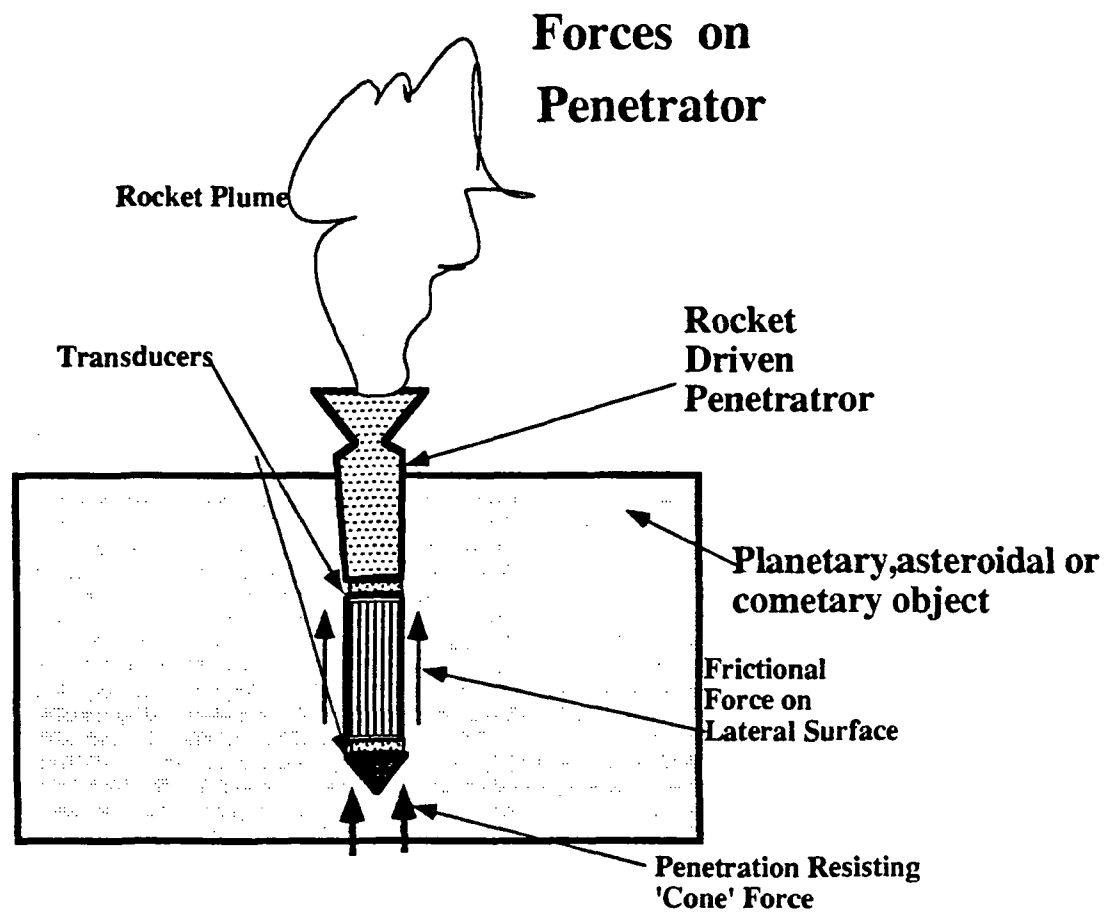


Fig. 6. Lateral and frictional longitudinal (cone) stress acting on planetary penetrator.

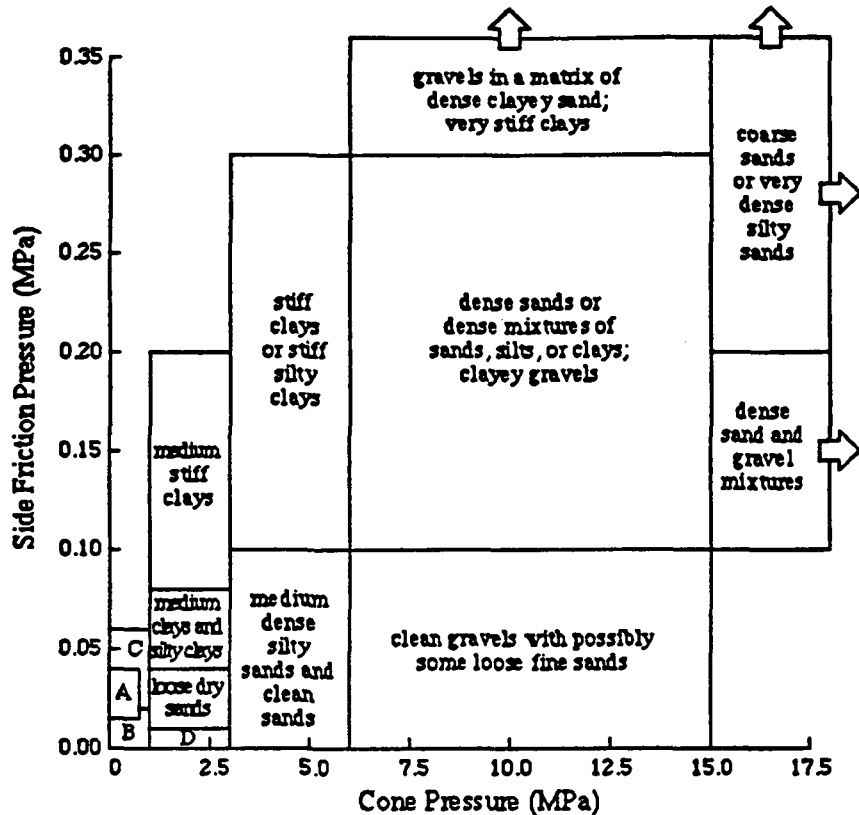


Fig. 7. (after Sanglerat [1972]) Relationship between cone pressure (penetration force per unit projected frontal area of the penetrator tip) and side friction pressure (friction force divided by surface area of friction sleeve) for quasi-static penetration into various terrestrial soil types. A; peats, lacustrine and very soft clays. B; loose silty sand and very loose fills. C; soft clays or silty clays. D; loose gravel fills. The cone pressure measured for permafrost (frozen ground; a possibly useful analog for cometary material) is ~10 MPa [Ladanyi, 1985]. Side friction measurements for permafrost are not yet reported.

IV. PERSONNEL

The proposed program will be directed by Thomas J. Ahrens, Principal Investigator, Professor of Geophysics (Curriculum Vitae - Appendix A). Theoretical modeling will be directed by Professor Ronald C. Scott, Professor of Solid Mechanics (Curriculum Vitae - Appendix B). They will be assisted by a Graduate Research Assistant. Technical support of a part-time technician, engineer, and machinist is also requested. In addition, some administrative and secretarial support is also requested in the Budget for preparation of technical presentations and scientific reports.

V. Budget - PLANETARY AND PRIMITIVE OBJECT APPARATUS

February 1, 1996 to January 31, 1997

	2/1/96- 1/31/97 -----
A) Salaries	
Dr. Thomas J. Ahrens, Professor of Geophysics, part-time	\$2,205
Dr. Ronald F. Scott, Doty and Dick Hayman Professor of Engineering, part-time	\$2,205
B) Graduate Research Assistant	\$14,333
Senior Technical Assistant, part-time	\$6,615
Senior Machinist, part-time	\$4,410
Secretary, part-time	\$3,308

Total Salaries	\$33,076
C) Staff Benefits - 34%	\$11,246
Total Salaries and Staff Benefits	\$44,322
D) Permanent Equipment	

Total Equipment	\$0
E) Travel	
One trip to scientific meeting	\$1,737
Airfare 1204	
4 days' per diem at \$112.5/day 450	
Travel in California	\$579
2,296 miles @ \$.24 (e.g. travel to suppliers, vendors, and apparatus repair establishments in Southern California)	

Total Travel	\$2,316
F) Computing	
Sun 4/110 at Seismo Lab Computing Facility	\$1,158
110/116 hrs. @ \$10/hr	

Total Computing	\$1,158
G) Expendables	
Transducers, cabling, film, metals, plastics, gases, epoxies, hardware, xeroxing, film, telephone, electronic equipment maintenance	\$7,663

Total Expendables	\$7,663

H) Total Direct Costs	\$55,459
I) Overhead - 58% of Total Direct Costs excluding equipment	\$32,166

J) Total Budget	\$87,625

Total 2 year request

VI. REFERENCES

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- Anderson, W. W., A. Gibson, K. Suzuki, T. J. Ahrens, and R. Scott, Emplacement of Penetrators into Planetary Surfaces, *JGR*, [submitted], 1995.
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- Melosh, H. J., Impact ejection, spallation, and the origin of meteorites, *Icarus*, 59, 234-260, 1984.
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- Sanglerat, G., *The Penetrometer and Soil Exploration*, 464 pp., Elsevier, New York, 1972.

VII. OTHER NASA SUPPORT (ANNUAL LEVEL)

Impact Cratering Calculations NAGW 1953, \$80,000

Cassini-Cosmic Dust Analyzer - JPL

Co-Investigator 49-567-85102-0-2400, \$40,000

Impact and Collisional Processes in the Solar System NAGW 1941, \$198,000

Curriculum Vitae

THOMAS J. AHRENS

Nationality: United States

Education:

B.S. (Geology-Geophysics) Massachusetts Institute of Technology, 1957

M.S. (Geophysics) California Institute of Technology, 1958

Ph.D. (Geophysics) Rensselaer Polytechnic Institute, 1962

Experience:

Geophysicist, Pan American Petroleum Corporation, 1958-59

Second Lieutenant, U.S. Army, Ballistics Research Laboratory, 1959-60

Geophysicist, Head Geophysics Section, Poulter Laboratory, Stanford Research Institute, 1962-67.

Conducted shock wave and impact experiments on rocks and minerals. Studied the effects of explosion in vacuo and explosive seismic coupling on the Moon. Discovered shock induced phase transitions in carbonates.

Associate Professor, California Institute of Technology, 1967-76.

Professor of Geophysics, 1976-present.

Supervised 21 Ph.D. graduate students and 27 Post-doctoral Research Fellows.

Recent Major Professional Service

Chairman, NASA Science Working Group, Comet Nucleus Sample Return Mission, 1985-1988; 1990-1991

Chairman, American Physical Society, Topical Group on Shock Compression of Condensed Matter, 1988-89

Convenor, American Geophysical Union Mineral Physics Workshop, 1988

Chairman, American Geophysical Union, Committee on Study of the Deep Earth's Interior, 1988-90

Editor, *Handbook of Physical Constants*, 1989-1995

Editorial Board, *High Pressure Research*, 1989-

NASA Lunar and Planetary Geosciences Review Panel 1990-1992

NSF Advisory Committee Earth Science Instrument and Facilities Program 1991-1992

Chairman, Advisory Committee, *Physics Today* 1992

Chairman, American Geophysical Union, Macelwane Award Committee 1992-1994

Editorial Board, *Physics of the Earth and Planetary Interiors*, 1992-

Editorial Board, *Planetary and Space Science*, 1992-

Member, Rosetta Surface Science Package Working Group, 1993-

Member, NASA, Small Bodies Science Working Group, 1993-

Convenor, CSEDI-LPI Conference on Deep Earth and Planetary Volatiles, 1994

Visiting Committees -

Department of Terrestrial Magnetism and Geophysical Laboratory, Carnegie Institution of Washington - Joint Visiting Committee 1989.

Center for Tectonics, University of California, Santa Cruz, 1987

Department of Geology and Geophysics, Princeton University, 1990-1993

Division of Earth and Planetary Science, Harvard University, 1990-

Max Planck Institut für Chemie, Mainz, Germany, 1993-

Division of Physical Science, University of Chicago, 1993

Geophysical Laboratory, Carnegie Institution of Washington, 1995-

Honors:

Fellow, American Geophysical Union, 1982

Newcomb-Cleveland Prize, American Association for the Advancement of Science, 1984.

Main Belt Asteroid - 4739, Tomahrens, 1985TH1, 1991

Member, U.S. National Academy of Sciences, 1992

Fellow, American Association for the Advancement of Science, 1994
Shock Compression Science Award, American Physical Society, 1995
Arthur L. Day Medal, Geological Society of America, 1995

Research Interests:

Dynamic response of solids. Impact cratering on planetary surfaces. In-situ stress measurements and high-pressure physics. Co-Investigator Cosmic Dust Experiment Cassini Mission. P.I. Physical Properties Probe, NASA/CNES Champollion Lander, Rosetta International Comet Mission.

Approximately 300 publications (abstracts excluded), 3 U.S. Patents

Papers pertinent to this proposal:

- Ahrens, T. J., and J. D. O'Keefe, Equation of state and impact-induced shock-wave attenuation on the Moon, in *Impact and Explosion Cratering*, edited by D. J. Roddy, et al., pp. 639-656, Pergamon, New York, 1977.
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- O'Keefe, J. D., and T. J. Ahrens, Impact and explosion crater ejecta, fragment size, and velocity, *Icarus*, 62, 328-338, 1985.
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- Rulison, A. J., R. C. Flagan, T. J. Ahrens, and W. F. Miller, Ablation of silicate particles in high speed continuum and transition flow with application to the collection of interplanetary dust particles, *Astrophys. J.*, 371, 432-442, 1991.
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- Ahrens, T. J., and A. M. Rubin, Impact-induced tensional failure in rock, *J. Geophys. Res.*, 98, 1185-1203, 1993.
- O'Keefe, J. D., and T. J. Ahrens, Planetary cratering mechanics, *J. Geophys. Res.*, 98, 17011-17028, 1993.
- Anderson, W. W., and T. J. Ahrens, Physics of interplanetary dust capture via impact into organic polymer foams, *J. Geophys. Res.*, 99, 2063-2071, 1994.
- He, H., and T. J. Ahrens, Mechanical properties of shock-damaged rocks, *Int. J. Rock Mech. Min. Sci. & Geomech. Abstr.*, 31, 525-533, 1994.
- Anderson, W. W., A. Gibson, K. Suzuki, T. J. Ahrens, and R. Scott, Emplacement of penetrators into planetary surfaces, *J. Geophys. Res.*, [submitted], 1995.

CURRICULUM VITAE

Ronald F. Scott

Education:

B.Sc. in Civil Engineering, Glasgow University, Scotland, 1951

S.M. in Civil Engineering, MIT, Cambridge, Mass., 1953

Sc.D. in Soil Mechanics, MIT, 1955

Experience:

1951–1953 — Full-time teaching assistant in Civil Engineering, MIT.

1953–1955 — Full-time research assistant, MIT.

1951–1955 — Employed by MIT Civil Engineering Faculty on a variety of soil mechanics consulting jobs.

1955–March 1957 — Soil engineer with U.S. Army Corps of Engineers, Arctic Construction and Frost Effects Laboratory, Boston, Massachusetts.

March 1957–October 1958 — Divisional Soil Engineer, Racey, McCallum and Associates, Toronto, Canada.

October 1958–1987 — Assistant, Associate and Full Professor of Civil Engineering, California Institute of Technology, Pasadena, California.

May 1987–Present — Dottie and Dick Hayman Professor of Engineering, California Institute of Technology, Pasadena, California.

Professional Activities:

Teaching of undergraduate and graduate classes in soil mechanics and foundation engineering and supervision of research in soil mechanics at Caltech.

Principal Investigator on lunar soil properties experiment on JPL (NASA) Surveyor spacecraft.

Member of soil mechanics team for Apollo manned lunar missions.

Member of Physical Properties team on NASA Viking (Mars 1976) spacecraft.

Consultant to private industry, local government, and U.S. Government agencies on a wide variety of soil engineering problems.

Special Interests:

Mechanics of deformation and yielding in soils

Soil behavior in earthquakes

Physical chemistry and mechanics of ocean-bottom soil

Lunar surface properties

Numerical solutions of soil mechanics equations

Physics and mathematics of freezing and thawing processes in soils

Memberships:

M, National Academy of Engineering (1974)
M, American Society of Civil Engineers
M, American Geophysical Union
M, Earthquake Engineering Research Institute
Registered Civil Engineer (No. C028240) in California

Publications:

Approximately 170 papers. Several Corps of Engineers published reports. Four books.

Patents:

Four U.S. Patents

Awards:

Walter Huber Research Prize, 1969, American Society of Civil Engineers
Norman Medal, 1972, American Society of Civil Engineers
Churchill Fellow, 1972, Cambridge University, England
Guggenheim Fellowship, 1973, Guggenheim Foundation
Newcomb Cleveland Award, 1976, American Association for the Advancement of Science
Thomas A. Middlebrooks Award, 1982, American Society of Civil Engineers
Terzaghi Lecturer, 1983, American Society of Civil Engineers
Rankine Lecturer, 1987, British Geotechnical Society

Personal:

Born in [REDACTED] Married, three sons.

Citizenship: U.S.A.

- 88.2 Scott, R. F., "Failure," Rankine Lecture, *Geotechnique*, **37** (4), 423–466, 1987.
- 88.3 Tan, T.-S. and R. F. Scott, "Finite Strain Consolidation—A Study of Convection," *Soils and Foundations*, **28** (2), 64–74, September 1988.
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- 88.5 Tagaya, K., R. F. Scott and H. Aboshi, "Pullout Resistance of Buried Anchor in Sand," *Soils and Foundations*, **28** (3), 114–130, September 1988.
- 89.1 Burridge, P. B., R. F. Scott and J. F. Hall, "Centrifuge Study of Faulting Effects on a Tunnel," *Journal of Geotechnical Engineering*, **115** (7), 949–967, July 1989.
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- 89.3 Scott, R. F., "Centrifuge and Modeling Technology: A Survey," *Revue Francaise de Geotechnique*, **48**, 15–34, 1989.(in French)
- 89.4 Scott, R. F., "Consolidation of Sensitive Clay as Phase Change Process," *Journal of Geotechnical Engineering*, **115** (10), 1439–1458, October 1989.
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